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Minimizing Fizeau fringes during the contact printing of diffraction gratings

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ABSTRACT

An index matching fluid has been used to minimize the effect of interference fringes which develop when contact printing diffraction gratings on silicon wafers. These fringes are the result of interference effects when there is a small but uneven gap between the photomask and resist surface. They are especially troublesome when printing and etching large area, coarse diffraction gratings on the surface of silicon wafers and silicon disks.

1.0 INTRODUCTION

Several photolithography techniques are available to print diffraction gratings on the surface of silicon wafers. The technique of choice depends on the period of the grating and its surface area. For a surface area less that 14 by 14 mm, and for a period greater than 2 µm, projection lithography is an obvious choice. For an area as big as 100 by 100 mm and a period greater than 5 µm, contact lithography is a good choice. These techniques are well covered in several texts on lithography.[1,2,3] For an arbitrary large area and a period as small as a few tenths of a micron, interference lithography should be used.[4,5] This paper discusses some unwanted effects that can happen during the contact printing of coarse diffraction gratings.

2.0 CONTACT LITHOGRAPHY

In this report we discuss the printing of large area, coarse gratings on silicon wafers or silicon disks, using contact lithography. In this application, the photomask used for printing has a 1x image of the grating. This photomask is held against the silicon wafer or disk. A vacuum fixture is usually used to get the best possible contact between the photomask and the resist coated silicon. It is very difficult to contact print these large area gratings without experiencing unwanted linewidth variations over the area of the grating caused by fringes that develop because of interference effects between the photomask and photoresist. This can be explained in a number of ways. First, consider the effect of not having a perfect contact between the photomask and surface of the photoresist. As explained on page 18 of Ref. #1 by Thompson, the minimum linewidth that can be printed in a grating is given by the following equation:

$$2b_{\min} = 3\sqrt{\lambda\left(g + \frac{d}{2}\right)} \qquad (1)$$

where:

b_{min}	minimum linewidth
λ	exposing wavelength

g photomask to resist gap
d photoresist thickness

For example, when using 405 nm exposing radiation, with a photoresist thickness (d) of 1000 nm, and no photoresist to mask gap (g = 0), the minimum linewidth (b_{min}) that can be printed is:

$$b_{\min} = \frac{3}{2}\sqrt{405\left(0 + \frac{1000}{2}\right)} = 675nm = 0.675\mu m$$

This minimum occurs because diffraction of the exposing light at the photomask hard surface causes interference effects within the photoresist. When contact printing a grating, the photoresist surface is not perfectly flat, and the photomask itself is not perfectly flat so the photomask to gap spacing (g) varies over the area of the grating. In areas where the photoresist to mask gap is 500 nm, the minimum printable linwidth is:

$$b_{\min} = \frac{3}{2}\sqrt{405\left(500 + \frac{1000}{2}\right)} = 955nm = 0.96\mu m$$

Consequently, the printable linewidth increases from 0.68 μm to 0.96 μm as the gap between the photomask increases from 0 μm to 0.5 μm. This variation can effect the quality of the resulting grating.

Another way to explain this variation in linewidth over the area of the grating is to observe the fizeau fringes[6] that can be seen visually during exposure. These are caused by interference effects in the gap between the photomask and the photoresist. At normal incidence, the condition for bright and dark fringes is:

$$2n_f t + \Delta_r = \begin{Bmatrix} m\lambda \\ (m+\frac{1}{2})\lambda \end{Bmatrix} \frac{bright}{dark} \qquad (2)$$

where:

- n_f index of the media between the photomask and photoresist. $n_f = 1.0$ if we assume a vacuum.
- t magnitude of the space between the photomask and the photoresist.
- λ wavelength of the exposing radiation.
- Δ_r 1/2 or 0 depending on whether there is or is not a phase shift of π between the interfering beams. For the example under study, $\Delta_r = 1/2$.
- m any positive integer

For our situation the increase in mask to resist gap (t) between two bright fringes is $\lambda/2 = 3000/2 = 1500$ Å. Wherever there is a bright fringe, energy is being reflected and not absorbed by the photoresist. Similarly, wherever there is a dark fringe, more energy is being absorbed by the photoresist. This pattern of more and/or less absorbed energy in the photoresist can lead to a variation in the grating linewidth over its surface and can affect the performance of the grating.

Figure 1 can be used to estimate the advantage of using an index matching fluid between the photomask and the surface of the photoresist. Essentially we are interested in comparing the peak to valley intensity variation due to the interference of (I_2) with (I_4) for the case of an air gap versus when an index matching liquid is used. This is not the only set of beams interfering at the top surface of the resist but it is the majority. To include more will make the calculated improvement of liquid versus air even bigger. For the index matching case, we will use the liquid Fluorinert which has an index of 1.28.

The reflectance (R) of light at an interface between two transparent materials with indecies of n_1 and n_2 is given by the following equation:

$$R = \left\{ \frac{(n_1 - n_2)}{(n_1 + n_2)} \right\}^2 \qquad (3)$$

If we assume coherent interference between beams (TID) and (TID2) shown in Fig.1, then the maximum and minimum intensity in the resulting fringes is given by:

$$\begin{aligned} I_{\max} &= I_2 + I_4 + 2\{(I_2)(I_4)\}^{0.5} \\ I_{\min} &= I_2 + I_4 - 2\{(I_2)(I_4)\}^{0.5} \end{aligned} \qquad (4)$$

From the above formulas we can calculate the reflectance of the various surfaces as follows:

	surface#	Incident	n_1	n_2	T%	TID	TID2	Imin	Imax
	0	1.000	1.00	1.50	0.960	0.960			
Dry	1	0.960	1.50	1.00	0.960	0.922			
	2	0.922	1.00	1.63	0.943	0.869	0.0020	0.79	0.87

	surface#	Incident	n_1	n_2	T%	TID	TID2	Imin	Imax
	0	1.000	1.00	1.50	0.960	0.960			
Wet	1	0.960	1.50	1.28	0.994	0.954			
	2	0.954	1.28	1.63	0.986	0.940	0.0001	0.92	0.94

Therefore, under dry conditions, the difference between the maximum and minnimum intensity of the interference fringes is (0.87 - 0.79) / 0.87 = 9.2%. The intensity difference under the wet conditions is less, and equal to (0.94 - 0.92) / 0.94 = 2.1%. This shows the advantage of using an index matching fluid in the small gaps between the photomask and the resist surface.

3.0 ERROR IN ETCHED SILICON GRATINGS

Recently there have been reports of blazed gratings etched into the hypotenuse of a right angled silicon prism[7,8]. These are called silicon grisms and they achieve a much higher resolution than ordinary reflective gratings[9]. Blazed silicon grisms can be conveniently fabricated by taking advantage of the anisotropic etching behavior of silicon in high pH solutions. If contact lithograph is used in the printing of the resist pattern for such a gating , the fizeau fringes mentioned above must be delt with or they can degrade the performance of the grating because of a resulting error in the placement of the grooves. Palmer et. al.,[10] have discussed the allowed magnitude of this error. They assume that no imperfection should contribute an error in the diffracted wave front of more than $\lambda/10$. With this assumption, they show that the error in placement of any groove should be less than d/10m where d is the grating period and m is the order in which the gating is used.

As an example, Ge[11,12]et. al. have used silicon grisms for high resolution infrared spectroscopy in an astronomy application. The area of the grisms is 10 by 10 sq. mm, the period is 66 μm, and they are used at a high order (m = 50). Under these conditions, the allowable error in the plcement of any groove is 66/10x50 = 0.13 μm. This error could very well be caused by the fizeau fringes which develop durng the printing.

4.0 EXPERIMENTAL RESULTS

Fizeau fringes seen in contact printing can be eliminated or at least minimized by using an index matching fluid as discussed above. Figure 1 is an optical photograph taken through a microscope of a grating photomask which has been vacuum clamped to a resist coated silicon wafer. The grating has a period of 100 μm. The fizeau fringes can be clearly seen. These fringes will cause slight variations in the printed linewidth which will be transferred to the etched silicon surface. Figure 2 is a ZYGO interferogram of the etched silicon grating. Variations in the diffracted wavefront, correspondng to the fizea fringes can be seen. Figure 3 shows the same grating photomask, again vacuum clamped to a resist coated silicon wafer, but this time with a fluid used between the wafer and the mask. No fringes are visible. The fluid used in this application was Fluorinert FC-77 made by 3M with an index of refraction of 1.28. This fluid does not react chemically with the resist.

5.0 DISCUSSION

The printing and etching of high quality echelle gratings on the surface of silicon wafers and silicon disks is a real challenge as discussed in some of the above references. Problems with surface smoothness, surface flatness and periodic and/or random groove placement errors can lead to unwanted scatter, poor efficiency and poor resolution. There are many processing details and material defects that must dealt with in order to achieve high performance gratings. In this paper we have identified yet another source for errors in gratings made by contact lithography. One must be aware of fizeau fringes which can form during contact lithography and lead to groove placement errors. It is shown that these grooves can be eliminated or minimized by the use of an index matching fluid. It should be pointed out that if a mask aligner is used for the contact print, the use of this index matching fluid can be rather messy and impractical. In our application a simple vacuum fixture was used for the contact print so there was no problem with the use of this liquid.

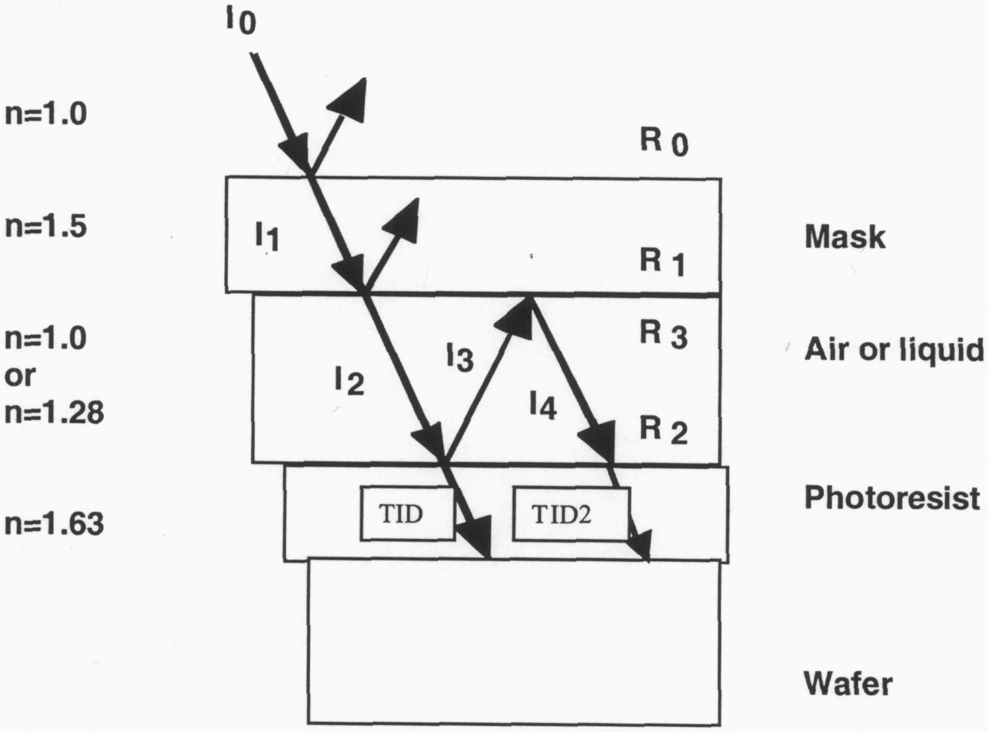

Fig. 1 Illustration of the reflections of the exposure energy in contact printing, when there is a gap between the photomask and the photoresist. The refractive index of each material is given on the left.

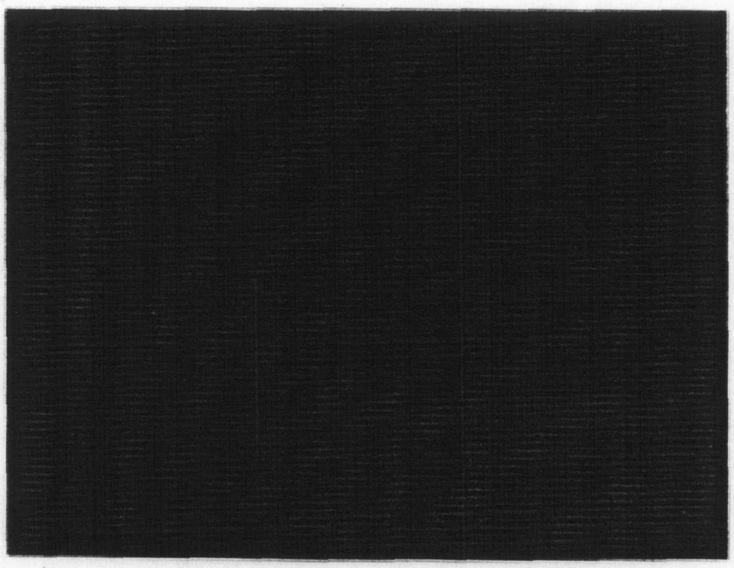

Fig. 2 Photograph of fizeau fringes. The grating on the photomask has a period of 100 μm and it is vacuum clamped to a resist coated silicon wafer with no index matching fluid.

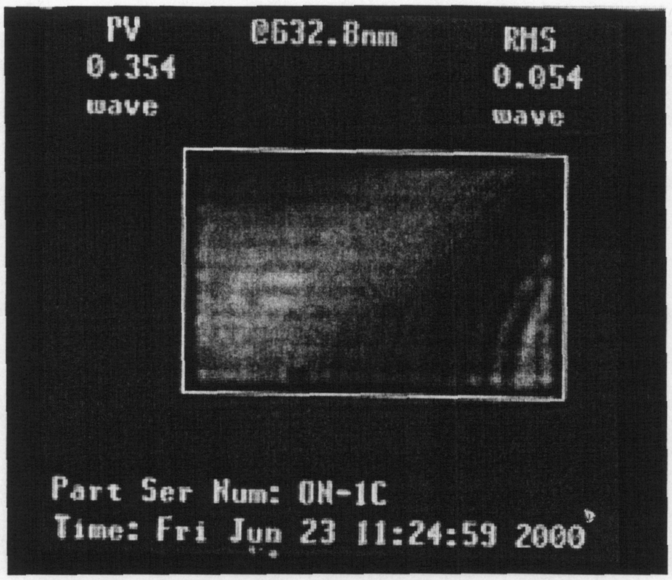

Fig. 3 ZYGO interferogram showing the wavefront distortion resulting from fizaeu finges during contact litography.

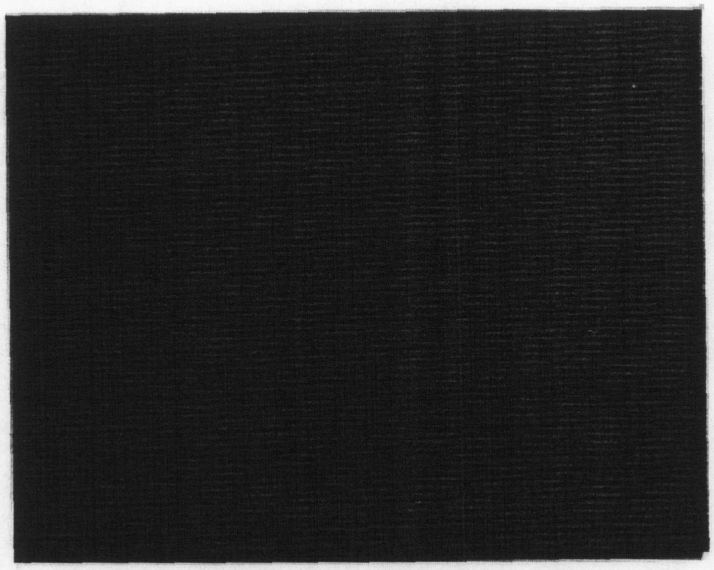

Fig. 4 Same condition as in Fig. 2 except this time there is an index matching fluid between the photomask and the silicon wafer. Cannot detect fizeau fringes.

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